

# **Advanced Kinetic-Based Modeling Applied to Plasma and Neutral Flows**

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# FRC thrusters: features and challenges



What is an FRC?

Derived from fusion technology

- Efficient plasma formation
- Gas independent (Air, Ar, Xe, Ne)

Cylindrical coil surrounding insulated discharge chamber

High speed transient B field generates azimuthal E field

Neutral gas injected into discharge chamber ionizes

Plasma is supersonically accelerated inward creating compression and heating (further ionization)

Toroidal plasma confinement

Plasma induces current which generates a magnetic field in opposite direction of applied field

Extreme pressure tends to drive plasma out of discharge chamber

Difficulties in modeling FRCs

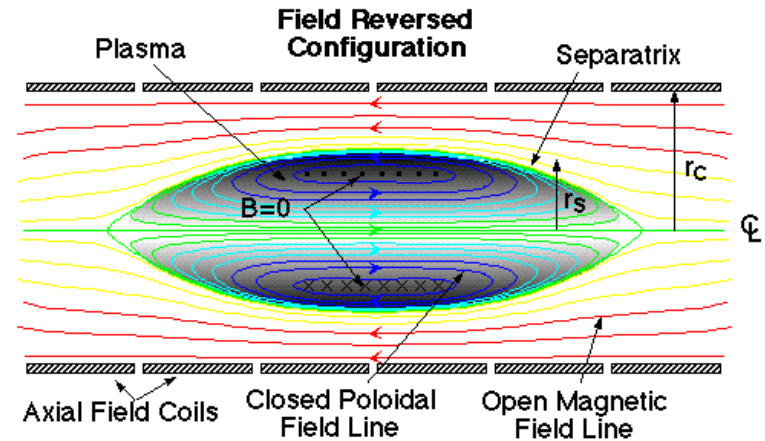
High density, MHD plasma

High temperature,  $T_e \sim 10 - 1000$  eV

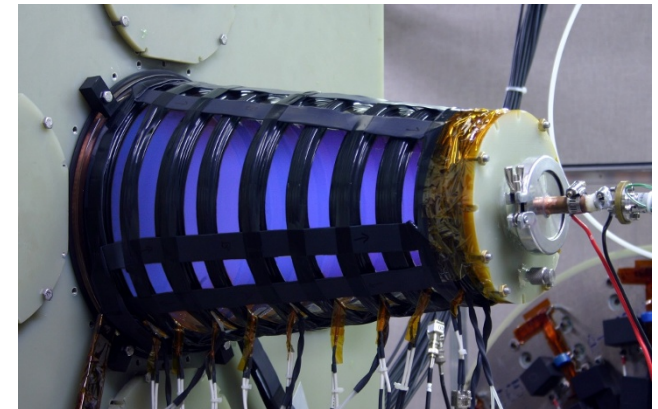
Non-equilibrium

Chemical (Air) / Ionization mechanisms

Neutral gas entrainment



## FRC schematics



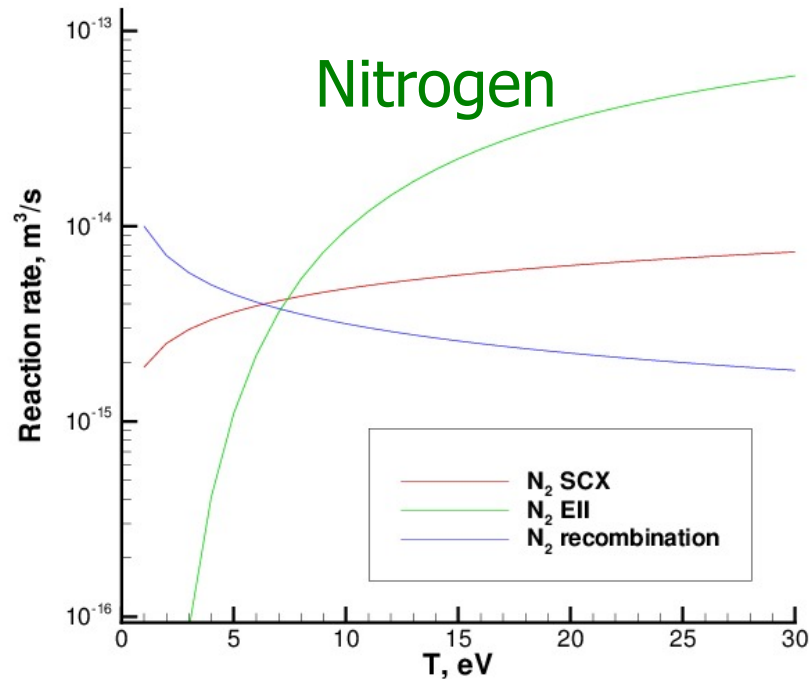
## MSNW FRC thruster



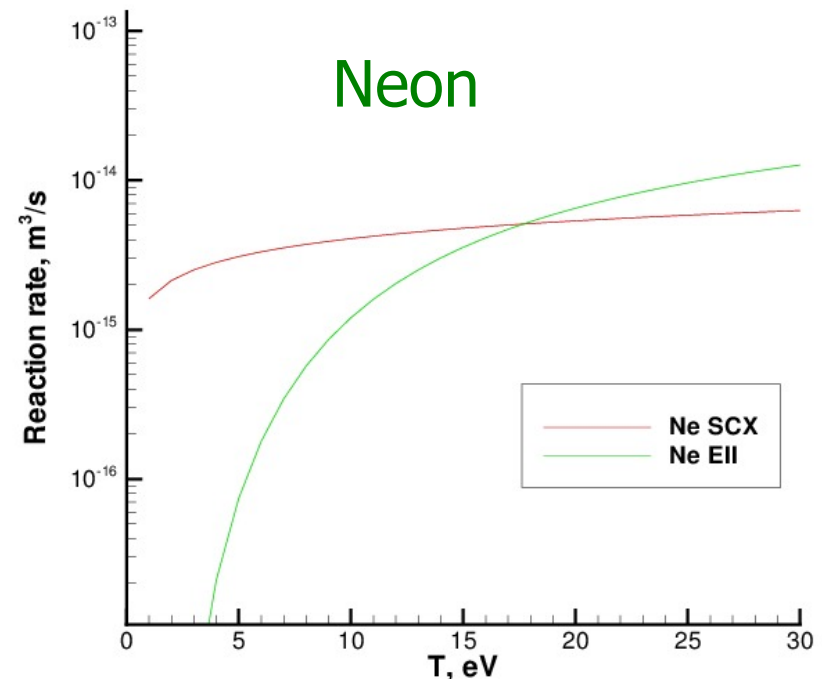
# FRC Neutral Entrainment: Reaction Rates



Included: electron impact ionization, single charge exchange, recombination



- Nitrogen: air breathing potential
- Recombination rate (dissociative recombination is included) dominates at  $T < 5\text{eV}$
- EII dominates at  $T > 5\text{eV}$
- May create problems for entrainment



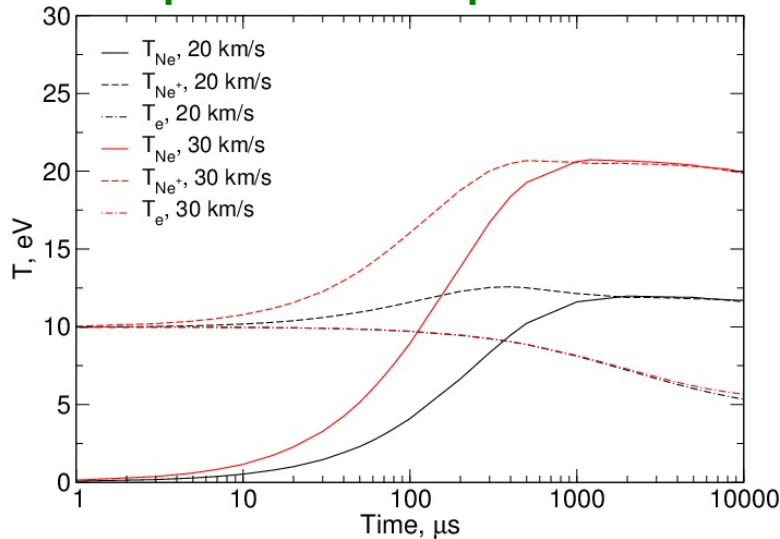
- Neon: high ionization energy
- Recombination (not shown) is not important
- SCX rate higher than EII, thus efficiency may be high
- Selected for further study



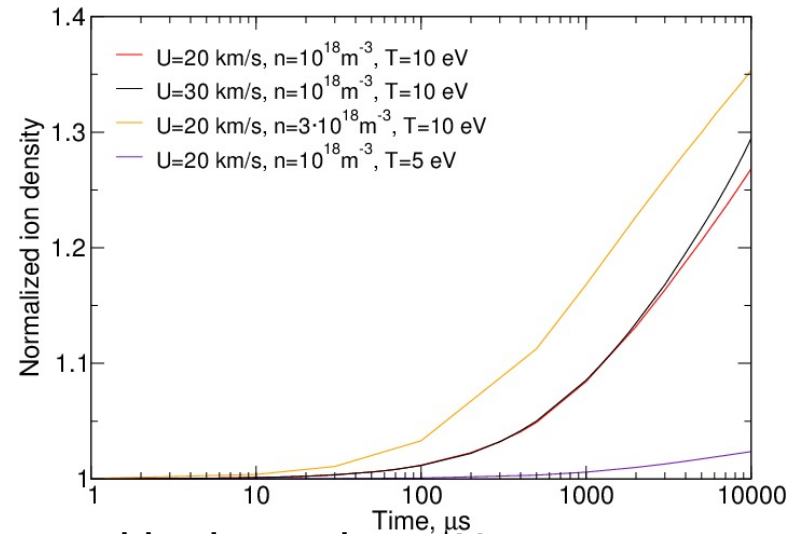
# Adiabatic Relaxation of Ne Plasma



## Species temperature



## Ion number density



- Energy of relative motion is converted into thermal, and T of heavy species increases
- Thermal relaxation of electrons on neutrals and ions is fairly slow
- Change in  $T_e$  is primarily related to the electron impact ionization reactions
- Impact of  $U$  on electron temperature becomes visible only after  $100\mu s$
- For any  $U$  and  $T$ , there is a strong thermal non-equilibrium
- $n_i$  weakly depends on  $U$
- Electron  $T$  is very important
- Number of charge exchange reactions for  $T=10\text{eV}$  and  $U=20\text{km/s}$  was found to linearly increase with neutral density
- The dependence of the number of ionization reactions on neutral density is weaker than linear
- Further increase slowed by the depletion of high energy electrons



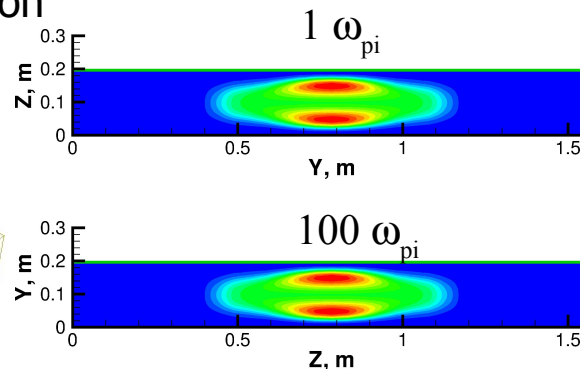
# Kinetic Modeling of Neutral Entrainment in FRC thrusters



**Goal:** develop a computational capability capable of accurate modeling of FRC neutral entrainment at kinetic level

- Celeste3D developed by J. Brackbill at Los Alamos selected as the main production and development tool: 3D PIC that solves the full set of Boltzmann-Vlasov eqns
- Benefits: kinetic (PIC based and thus amenable to DSMC-like neutral addition), implicit (large time steps allow modeling of neutral entrainment), full 3D
- Physical challenges: plasmoid formation & translation, neutral capability addition, open boundary conditions, many physical and chemical processes
- Numerical challenges: multi-processor domain decomposition parallelization, adding flexible initial conditions and non-rectangular geometries

Ion density evolution



## Progress:

Neutral entrainment modules  
Arbitrary initial condition capability  
Plasmoid / neutral interaction  
Open boundary conditions



# Modified Celeste3D



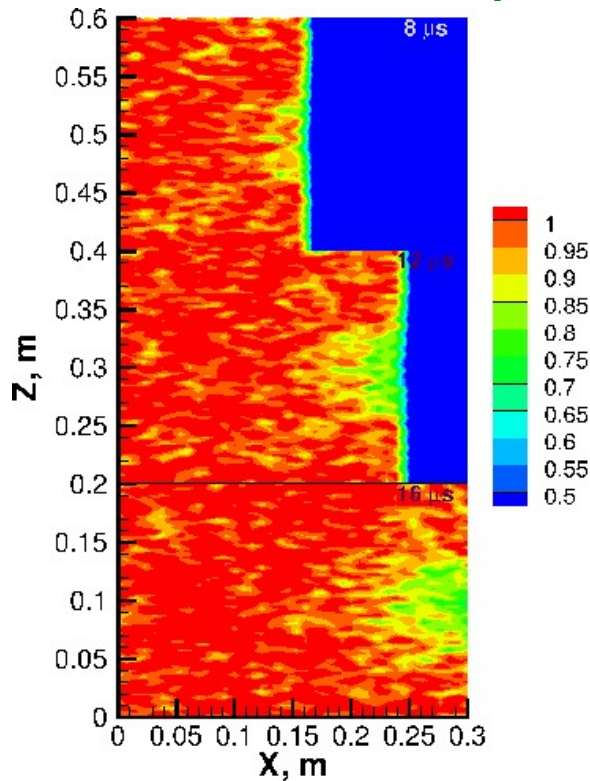
- Extended to include neutral transport and collisional relaxation
- Particle-based kinetic capability includes the following **collisional processes**:
  - ➔ neutral-neutral collisions (VHS model)
  - ➔ charge exchange reactions (Losev's cross sections)
  - ➔ neutral-ion elastic collisions (according to Losev)
  - ➔ the electron impact ionization (SIGLO)
- Hard sphere after-collision scattering is assumed for all these processes, with the exception of charge exchange reactions, for which the velocities of neutrals and ions are swapped
- Species weighting scheme is implemented
- Majorant collision frequency scheme in spatial cells
- **Coulomb collision** module has been added to Celeste, based on a particle-weights scheme of Nanbu



# 5eV Plasmoid Evolution

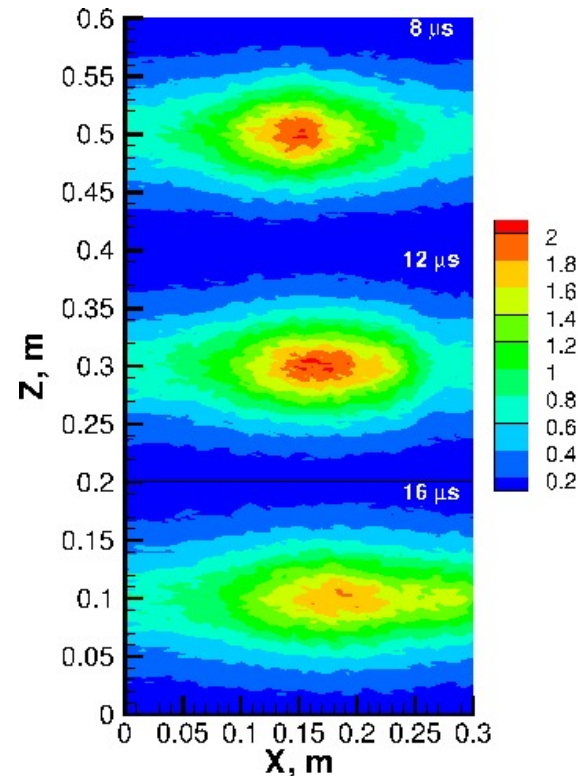


## Neutral density



- At 16  $\mu$ s, neutrals loss near the centerline amounts to about 30%
- Loss of neutrals = gain in ions

## Ion density



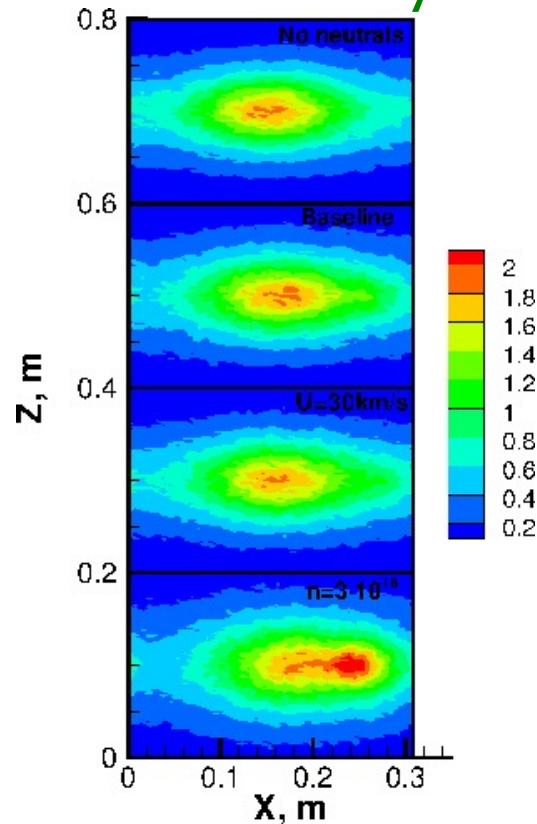
- 8ms: impact of neutrals is negligible
- 12ms: moderate, on the order of 5%, increase in plasma density in the center
- 16ms: plasma density in the center decreases due to mass transfer
- Significant elongation of the plasmoid



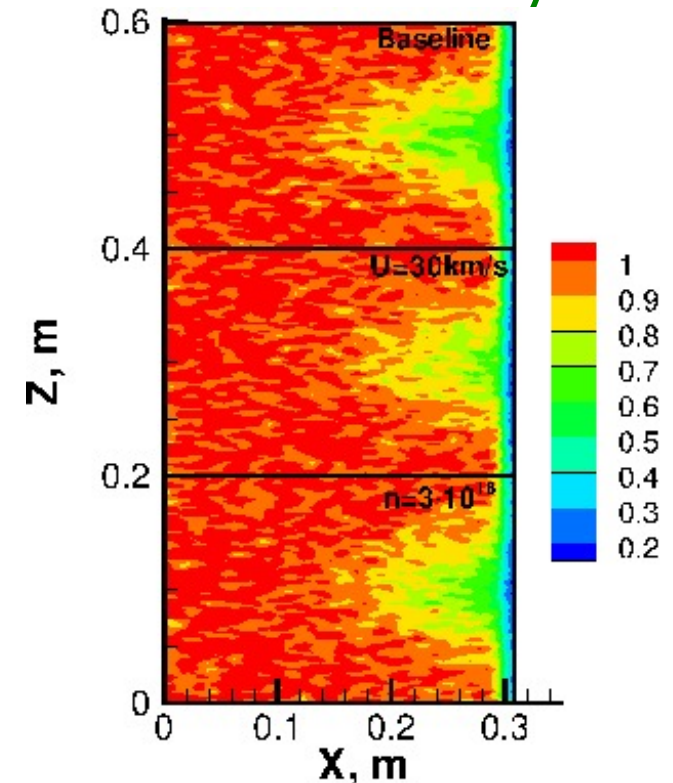
# 10eV Plasmoid Evolution



## Ion density



## Neutral density



- Baseline: modest( $\sim 5\%$ ) increase in  $n_i$
- Clear translation of the plasmoid
- Average velocity of initially stationary plasmoid is about 3km/s
- $U=30km/s$ : weaker interaction (short  $t$ )
- Larger  $n$ :  $p$  transfer, ionization triple

- Neutral density decreases by  $\sim 50\%$  for the baseline and  $\sim 30\%$  for  $U=30km/s$
- Since change in  $n_i$  is  $<$  change in  $n_n$ , the latter is related to charge exchange
- Neutrals lose  $x$  momentum after charge exchange, and do not reach right boundary



# Summary



- First step toward accurate modeling of FRC thruster with neutral entrainment
- Comparison of ionization and charge exchange **reaction rates** indicates that the use of nitrogen and especially xenon may be problematic, while neon appears to be a fairly good propellant
- **Adiabatic heat bath:**
  - showed that FRC entrainment proceeds under conditions of strong thermal and chemical non-equilibrium; ion, electron, and neutral temperatures strongly differ, and the electron distribution function is non-Maxwellian
  - Strong impact of electron temperature on plasma density due to ionization
  - Modeling of Coulomb collisions between electrons is desirable to properly account for electron high velocity tail depletion
- **2D modeling:**
  - Implicit PIC code Celeste3D extended to include neutral transport, plasma-neutral and neutral-neutral collisions and Coulomb collisions
  - For 5eV and 10eV, strong entrainment of neutral particles by a translated plasmoid is observed as a result of charge exchange reactions between slow neutrals and fast moving ions
  - Modest increase in plasma density due to electron impact ionization
  - Increase in neutral density appears highly beneficial for thruster efficiency



# FY12 Publications and Outlook



- 7 journal articles (Physics of Fluids, Applied Physics Letters, Optics Express, International Journal of Computational Fluid Dynamics, Vacuum, Journal of Applied Physics, Journal of Chemical Physics)
- About 15 refereed conference presentations/papers (AIAA conferences and RGD Symposium)
- Future directions in kinetic modeling of FRC thrusters:
  - ➔ Electronic excitation
  - ➔ Air breathing
  - ➔ 3D and annular configurations
  - ➔ RMF, plasmoid formation
  - ➔ Parallelization